

**AIAA AVIATION 2016: INVITED SESSION**

**SESSION 264-FD-60: IDENTIFYING THE IMPACT OF NON-EQUILIBRIUM MECHANISMS IN ENGINEERING FLOWS**

# **Aerospace Applications of Non-Equilibrium Plasma**

by

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Session FD-60: **“Identifying the Impact of Non-Equilibrium Mechanisms on Engineering Flows”.**

Title: **Aero-propulsion Applications of Non-equilibrium Plasma.**

## **ABSTRACT**

Nonequilibrium plasma/non-thermal plasma/cold plasmas are being used in a wide range of new applications in aeronautics, active flow control, heat transfer reduction, plasma-assisted ignition and combustion, noise suppression, and power generation. Industrial applications may be found in pollution control, materials surface treatment, and water purification. In order for these plasma processes to become practical, efficient means of ionization are necessary. A primary challenge for these applications is to create a desired non-equilibrium plasma in air by preventing the discharge from transitioning into an arc. Of particular interest is the impact on simulations and experimental data with and without detailed consideration of non-equilibrium effects, and the consequences of neglecting non-equilibrium. This presentation will provide, via the use of specific examples, the reasons for choosing nonequilibrium plasma, and an assessment of the presence and influence of non-equilibrium phenomena for various aerospace needs and applications. Specific examples include the forward energy deposition of laser-induced non-equilibrium plasmoids for sonic boom mitigation, weakly ionized flows obtained from pulsed nanosecond discharges for an annular Hall type MHD generator duct for turbojet energy bypass, and fundamental mechanisms affecting the design and operation of novel plasma-assisted reactive systems in dielectric liquids (water purification, in-pipe modification of fuels, etc).

# **FOCUS: NON-EQUILIBRIUM PLASMA/MHD** **TOPICS FOR DISCUSSION..**

**Nonequilibrium/no-thermal plasmas are in use in Aerospace applications such as active flow control, heat transfer reduction, ignition/combustion, noise suppression, and power generation. Industrial applications include pollution control, surface treatment, etc**

- (1) MHD-controlled turbojet – non-equilibrium ionization of free-stream. Pulser-Sustainer Technique.**
- (2) Sonic Boom Mitigation by forward non-equilibrium plasma energy deposition. Control of shock-wave patterns.**
- (3) Space mission application: Non-equilibrium plasma water purification supporting human space flight.  
(Part of “Injection of Repetitive High-Voltage Nanosecond Plasma in dielectric liquids (water, hydrocarbon fuels, etc)”.**
- (4) PLASMA-ASSISTED Combustion and Kinetics (Partnership activity/OSU):**

# Activities in Plasma Laboratory (VF69)

Understand the physics of the cold, non-equilibrium plasma generation in air and provide data for a multi-temperature model development to be used for evaluating its effectiveness in hypersonic flow control of **MHD-engine**, heat transfer reduction, power generation, and noise suppression.

## Generation of Plasma with FIW

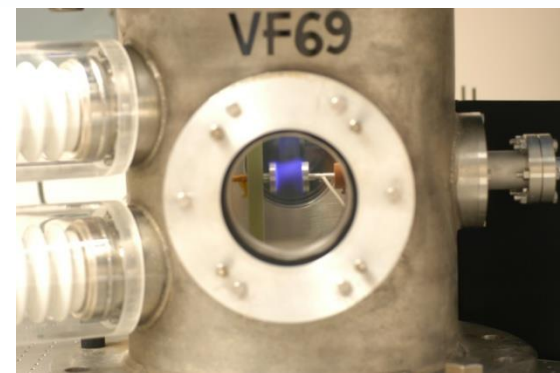


Plasma

Top View

## “PULSER-SUSTAINER” TECHNIQUE CHOSEN FOR PLASMA GENERATION.

- Sub-atmospheric conditions set by **Mach 7 flight at 30 km**
- Cage with mechanical pump and dry air source assembled for 10 to 80 Torr



## High Voltage Pulsed Power Supplies (FIW):

- High voltage **pulser** power supply with 10 to 100 kV amplitude, 2 ns rise, 2 to 5 ns width, 3 ns fall, and 6 to 100 kHz repetition rate.
- 2<sup>nd</sup> **pulser** power supply : 10 to 40 kV amplitude, 2 ns rise, 20ns width, 3 ns fall, and 6 to 100 kHz repetition rate.
- **Sustainer** floating power supply with 2 kV and 3 A

## A FEW RESULTS FROM PLASMA LAB (BLDG 16/VF69)

(Lab is focused on the exploration of nonequilibrium ionization by non-thermal means with application to hypersonic and supersonic vehicles)

- **Main Power supply produces High-Voltage nanosecond (2 to 5 nsec) discharges generating weakly-ionized plasma.** The spatially uniform and highly nonequilibrium plasma is obtained and sustained by combining pulse nanosecond discharge with sustainer DC voltage.
- **High E-field in ionization wavefront** provides a means to energize and sustain high-energy electrons while maintaining a lower nearly constant ion/molecule temperature. Major fraction of electrical discharge power goes into vibrational excitation of **N<sub>2</sub>**.
- **Demonstrated lifetime of sustainer discharge current** is 10-25 microseconds – i.e. 3 orders of magnitude longer than the 5nsec pulse width. Lifetimes are adequate for exploiting weakly-ionized gas flows in inlets, combustors, nozzles.
- Pulse duration < < **ionization instability** development time ( ~ microsecond).
- **Thermalization and breakdown** are avoided through the application of short high-voltage repetitive pulses.
- **Energy consumption** ~ 200 -700 Watts depending on pulse repetition rate.

(Detailed results will be found in AIAA Paper 2009-1050)

# (I) MHD-CONTROLLED TURBOJET

## A NEW ROLE FOR NON-EQUILIBRIUM PLASMA AND MHD (MAGNETOHYDRODYNAMICS) FOR A **FLIGHT-WEIGHT** ENGINE

**Approach:** Bypass part of the inlet **kinetic energy** and **enthalpy** via MHD for conversion into electrical power. Serves three aeropulsion purposes:

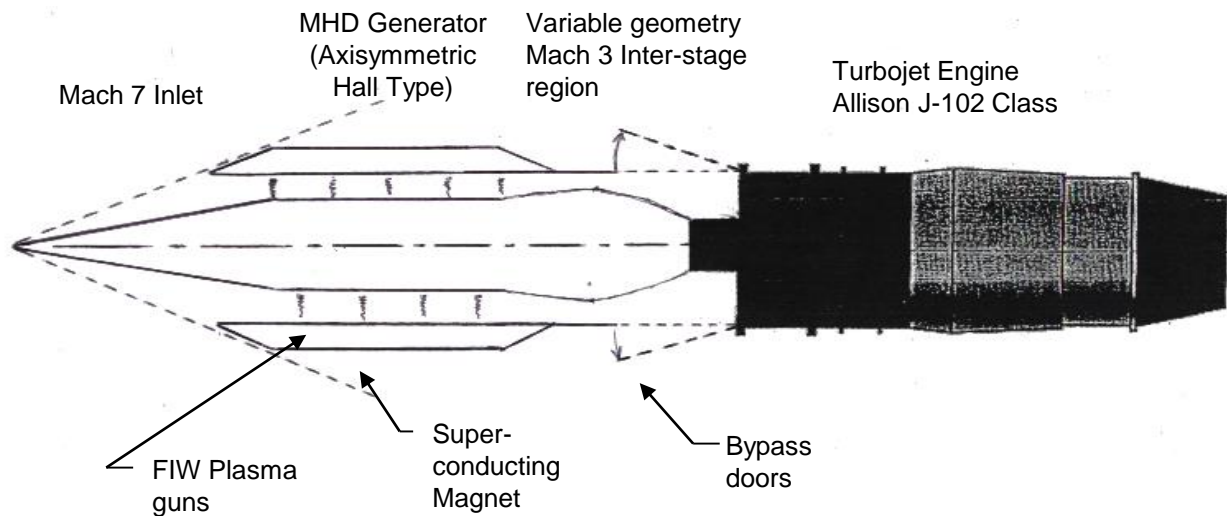
- (1) Enthalpy into combustor is reduced – hence more efficient addition of energy in combustor without exceeding material limits.
- (2) Applied E-Fields/Lorentz force can enhance off-design performance – manipulate inlets flow, reduce total pressure losses
- (3) Electrical power removed can be used for various on-board vehicle purposes.

### Method of Ionization:

Efficient **nonequilibrium ionization using non-thermal** methods to be used to achieve adequate conductivity in a weakly-ionized plasma. **High-voltage nanosecond pulser-sustainer discharge plasma** method selected.

Electron beam approach (implementation) considered impractical for this application.

# MHD-Controlled Turbojet Engine Concept: Planned Experiment in NASA Wind-Tunnel using Allison J-102



MHD Power Extraction Patent

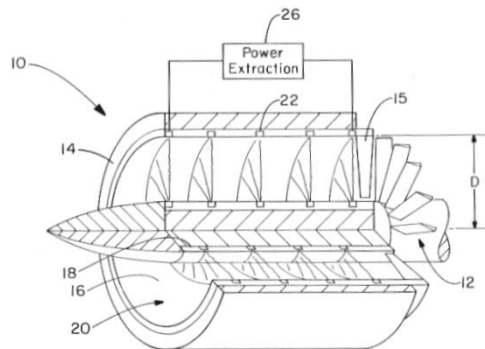
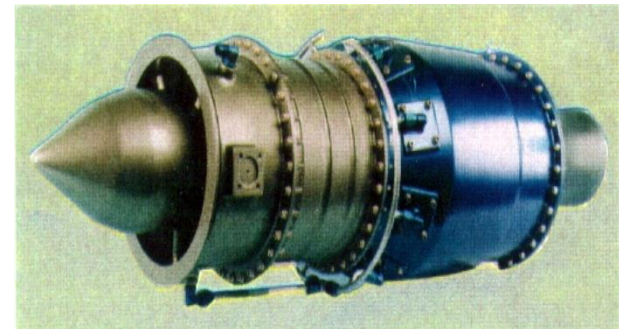


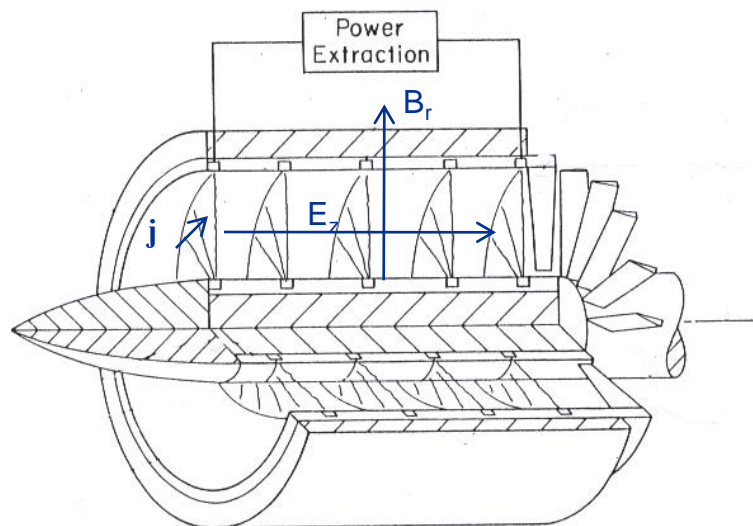
FIG.-1



**Annular Hall -Type MHD Generator: Based on Hall thruster Design for Space and Fast Ionization Wave non-equilibrium plasma generation. US Patent (6,696,774 B1; 2004)**



# Annular MHD Hall Generator Concept



- Geometrically compatible with a turbojet
- Current spirals down the flow path setting up an axial Hall electric field tapped for power extraction/addition
- Conductivity established by non-equilibrium ionization (not alkali metal addition)
- Geometry **already used on the Russian Stationary Plasma Thruster for space propulsion**
- Geometry explored for combustion-driven MHD power generation in the 1930s to 1950s (K and H generator)
- Concept offers the potential for a single flow path to Mach 7+ without mechanical mode transitions
  - Electrically maintained enthalpy

**Annular Hall –Type MHD Generator: Based on Hall thruster Design for Space and Fast Ionization Wave non-equilibrium plasma generation. US Patent (6,696,774 B1; 2004)**



# SHORTCOMINGS OF OUR PREVIOUS COMPUTER SIMULATION:

## CODES AVAILABLE FOR FUTURE WORK

- **(1) MACH2 Code Simulation: For Weakly-Ionized Gas. (2.5-D)**
- Time-dependent, 2- D axi-symmetric simulation tool for complex planar or cylindrical geometries. Quasi-neutral, Viscous Compressible Fluid with Elastic-plastic Package, Ablation Models and Multi-Material Capability. **Park non-equilibrium model.**
- Multi-temperature: Electron, Ion, Radiation . Various Radiation Models With Real Semi-empirical Opacities.
- Resistive-Hall-MHD with Braginskii Transport, Multi-ported Circuit Solver (e.g. LRC, PFN), Various Models For Anomalous Resistivity and Electron-Neutral Contributions
- Analytic or Real Semi-empirical (SESAME) Equations of State, LTE Ionization State
- **(2) OSU NON-EQUILIBRIUM FLOW CODE ( 1-D )**
- Master equation for vibrational populations of  $N_2$  and  $O_2$ . Boltzmann equation for electrons.
- Nonequilibrium air chemistry including ion-molecule reactions
- Nonequilibrium electron kinetics (ionization, recombination, and attachment)
- 1 – D Gas dynamics. Generalized Ohm's law.
- Validated by comparing with electric discharge, shock tube, and MHD experiments
- **(3) IN-HOUSE ENGINEERING CODE (MATLAB): 1 - D Axisymmetric** (equations with large radius approximation/small gap gives a **meanline** generator/accelerator design.)
- “MHD approximation “to fundamental equations of plasma dynamics (Low Magnetic Reynolds Number, Maxwell's Equations unaffected by gasdynamic motion, magnetic field induced by fluid motion negligible compared to applied Magnetic Field). **Hall effect and Ion-Slip terms included..**  
Approach from DOE MHD generator program: Assumes steady state “Plasma Dynamics” using the conservation laws and conductivity. No detailed plasma kinetics!

# Annular MHD Hall Generator Design

Inlet conditions:

$$M = 5.02$$

$$P_s = 32.7 \text{ Torr}$$

$$T_s = 420^\circ\text{K}$$

Generator parameters:

$$B_r = 5 \text{ Tesla}$$

$$\sigma = 5 \text{ mho/m}$$

$$L = 3 \text{ m}$$

$$K_h = -0.09$$

$$d(\rho v_z)/dz = -21 \text{ kg/m}^3\text{-s}$$

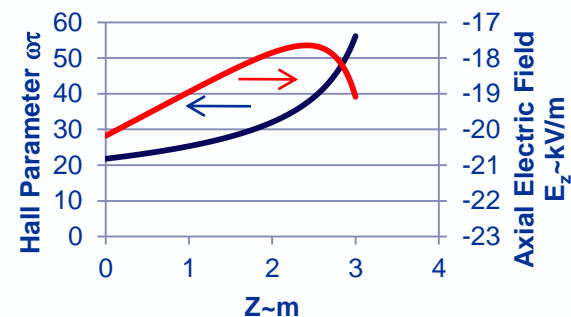
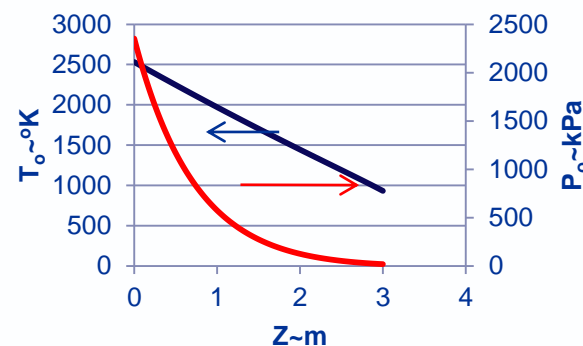
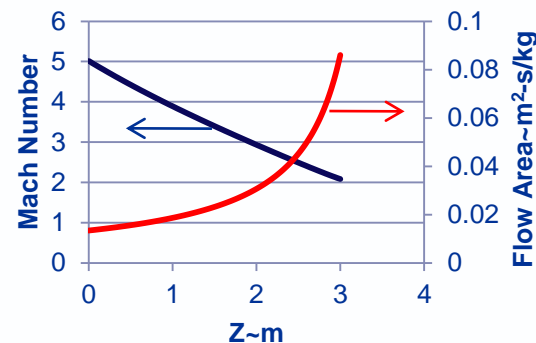
$$\eta_{Ng} = 0.63$$

$$\eta_s = 0.84$$

$$V = 55.8 \text{ kV}$$

$$I = 28.7 \text{ Amp/kg/s}$$

$$P_e = 1.60 \text{ MW/kg/s}$$



# Preliminary Results (AIAA 2003-4289)

## MHD Bypass Engine Application – OSU Code Evaluation

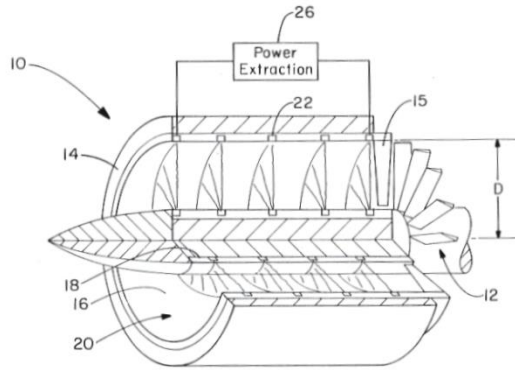
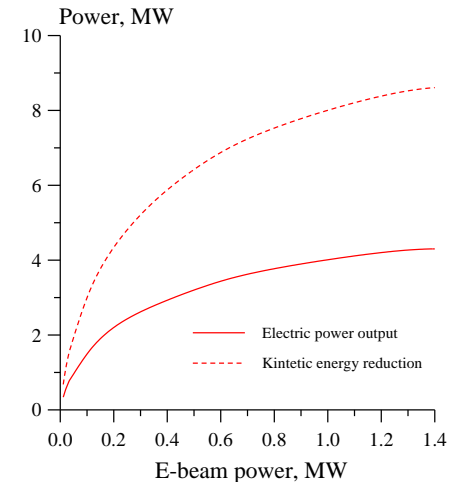
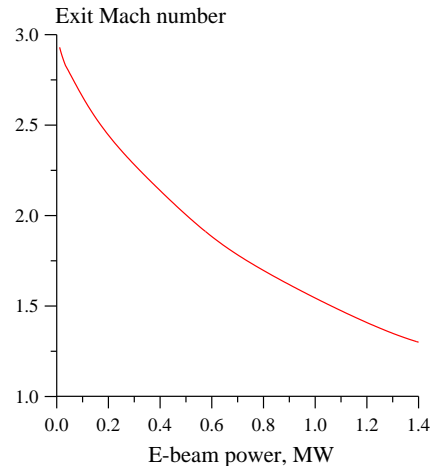


FIG.-1



- OSU quasi-1D, nonequilibrium MHD air flow code used
- Ionization by uniformly distributed e-beam (need simulation with pulsed ionizer)
- Realistic E-beam power 0.11 MW (20 keV electron beam, 0.2 mA/cm<sup>2</sup>)
- 10 Tesla magnetic field

- Substantial reduction in the kinetic energy of supersonic flow is possible
- 50% Conversion of kinetic energy to electrical power predicted

# Non-equilibrium Ionization Assessment

- **Pulser-sustainer discharge<sup>1</sup> ionization process using nanosecond pulses is proposed as the means for the non-thermal ionization**
  - Energizes and sustains electrons at a high  $T_e$  while maintaining a low nearly constant ion/neutral temperature  $T_s$
  - $\sigma=1.0 - 5.0$  mho/m requires an  $n_e/n=1.90 \times 10^{-6} - 9.52 \times 10^{-6}$  for  $T_e=1\text{ev}^1$
  - Initial cage tests<sup>2,3</sup> indicate an ionization fraction  $1.1 \times 10^{-8}$  at 50 Torr

Lifetime of sustainer discharge current 10-25 microseconds. 3 orders of magnitude longer than the 5 nsec pulse.
- Annular Hall type MHD Generator/Accelerator operation
  - **Azimuthal current could act like a sustainer current to keep  $T_e$  elevated**
  - Non-thermal ionization facilitates MHD interaction with the core flow since the boundary layers won't have a higher conductivity

- 1) Nishihara, M., Rich, J. W., Lempert, W. R., Adamovich, I. V., and Gogineni, S., "Low-Temperature M=3 Flow Deceleration by Lorentz Force", Physics of Fluids, Vol. 18, No. 8, August 2006, pp. 086 101-086-111
- 2) Schneider, S.J., Kamhawi, H., and Blankson, I.M., "Efficient Ionization Investigation for Flow Control and Energy Extraction", AIAA-2009-1050, 47<sup>th</sup> AIAA Aerospace Sciences Meeting, Orlando, FL, January 5-8, 2009.
- 3) Blankson, I., Schneider, S., AIAA Paper 2003-6922, presented at 12<sup>th</sup> AIAA International Space Planes and Hypersonic Systems Conference, 15-19 December, 2003/Norfolk, VA.

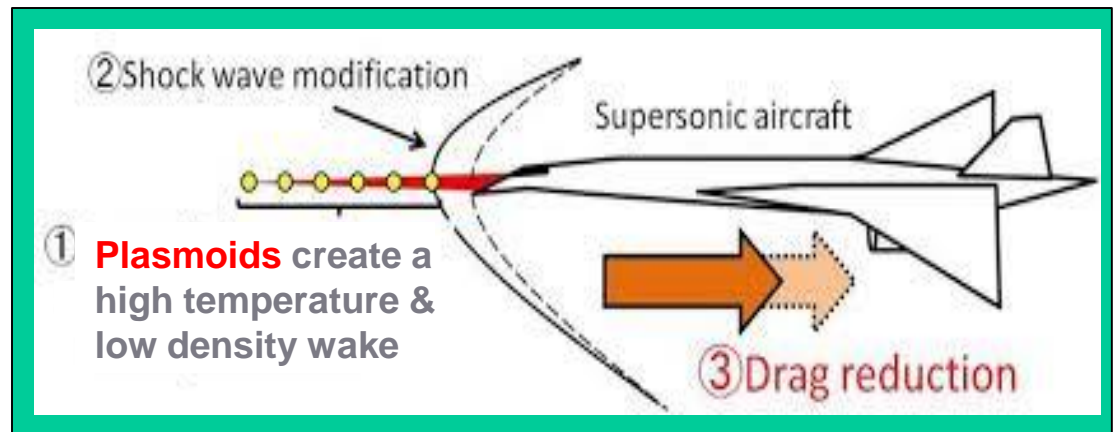
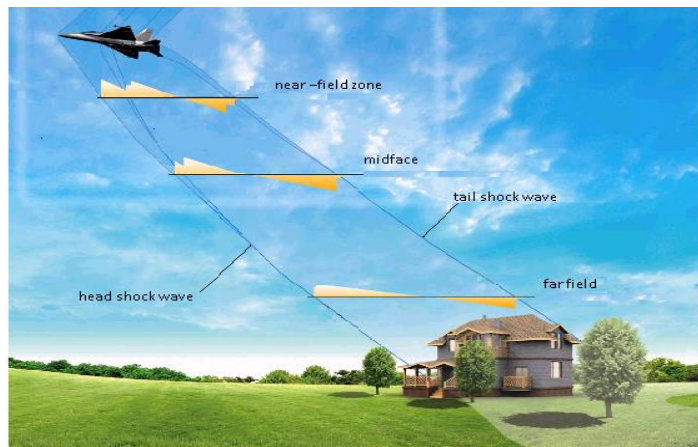
## (II) Mitigation of the Sonic Boom by **Pulsed** Forward Plasma Energy Deposition: An **Active** Suppression Method

### PROJECT OBJECTIVES:

Demonstrate the reduction/mitigation of the sonic boom generated in supersonic flight, by **modifying/manipulating the oncoming flow** using **active forward energy deposition** in the form of a plasma discharge (plasmoids) ahead or within the bow shockwave.

The plasma to be produced by a pulsed focused-laser beam-strike upstream of the vehicle.

**(MAX ground overpressure of 0.3 psf)**

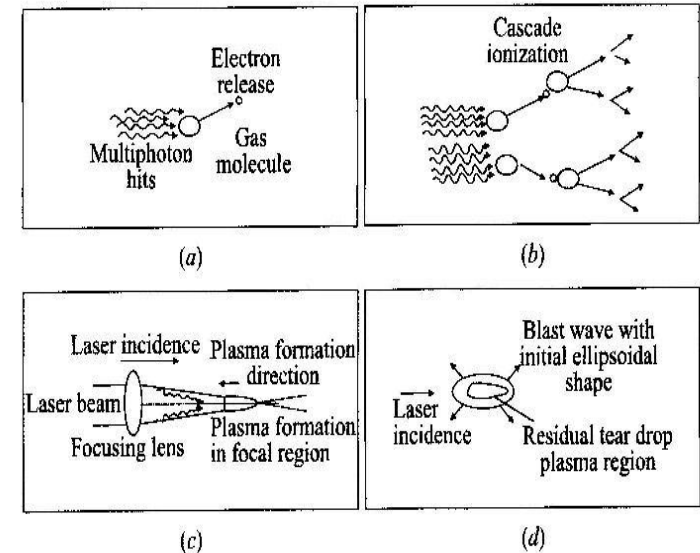


The particular application to sonic boom reduction requires laser-induced plasma be deposited far upstream of vehicle.

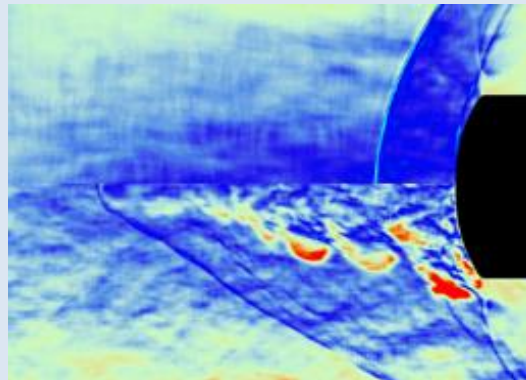
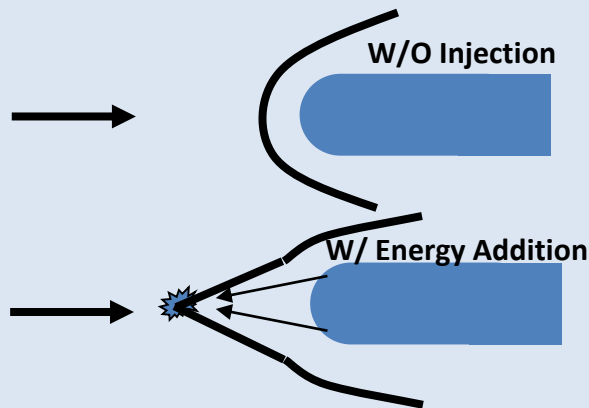
Energy deposition scheme must not interfere with the mass flow and air chemistry into vehicle's air-breathing engines.

# Energy Deposition into a Gas by Focused Laser Beam-the physics

- A laser beam strongly focused can be used to ionize and heat gas locally
  - **Typical Power Density  $>10^{12}$  W/cm<sup>2</sup>**
- Three basic mechanisms for plasma formation
  - Field ionization
  - Multiphoton ionization (initial release of electrons)
  - Cascade driven ionization
- Laser produced plasma offer a compelling solution to heating or modifying shock structure
  - Energy imparted to electrons non-thermally then couples to neutrals via collisions thus heating the gas (more efficient energy transfer than heating bulk gas)
- To generate filament, laser is tightly focused to achieve high field. Pulse duration is short to force a large number of photons into the tightly focused spot (fs time scales ideal)



## Laser-Induced Plasma Application to Flow Control: Wave-Drag Reduction



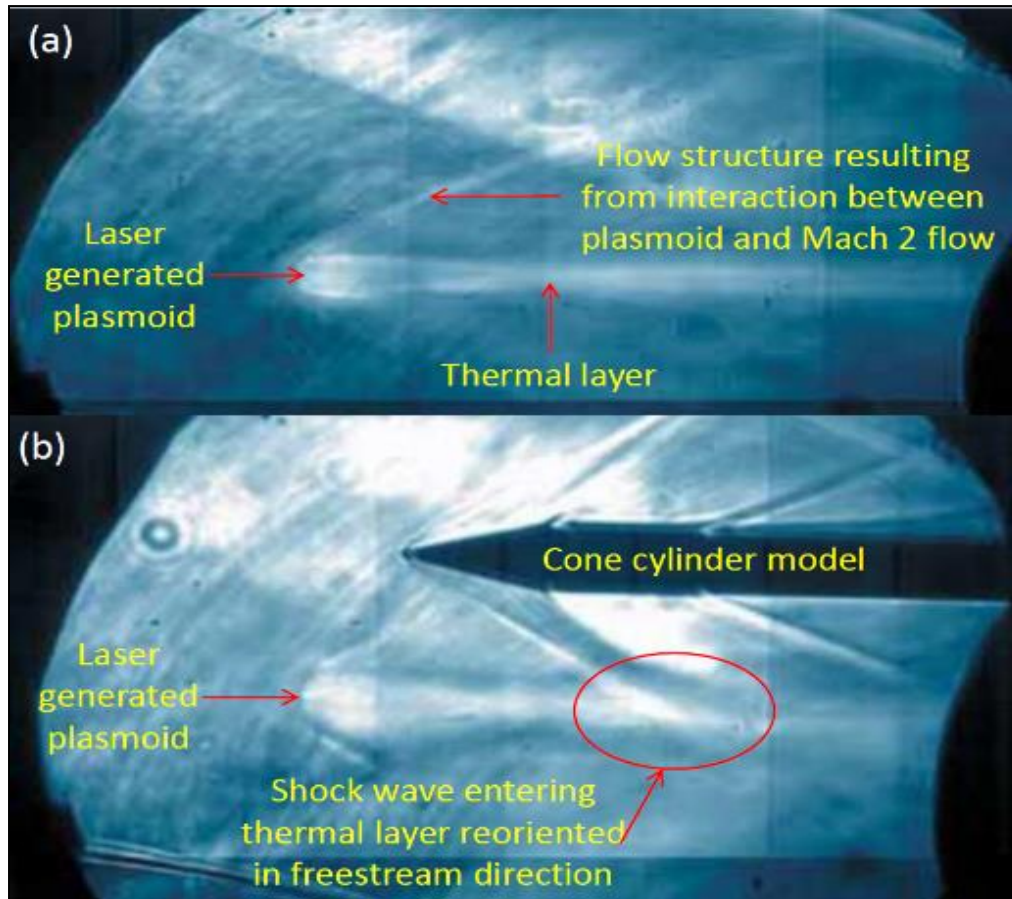
Schlieren images of the shockwave in front of a supersonic model:

- upper semi-picture - **WITHOUT**
  - lower semi-picture - **WITH**
- laser induced energy deposition.

The drag reduction that has been proven by these experimental investigations and numerical modelling is, presumably, caused by local heating of the gas flow



# Interaction of Pulsed Laser Plasmoid with an Oncoming Supersonic Flow



Plasmoids can be generated at various locations.

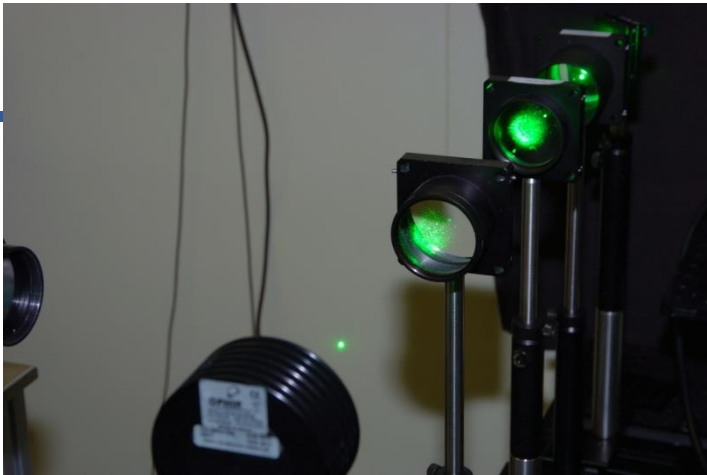
Plasmoids introduced directly ahead of body: **Shockwave is distorted and weakened.**

Plasmoid introduced below body: **Shockwaves entering The thermal layer are re-oriented in the free-stream direction.**

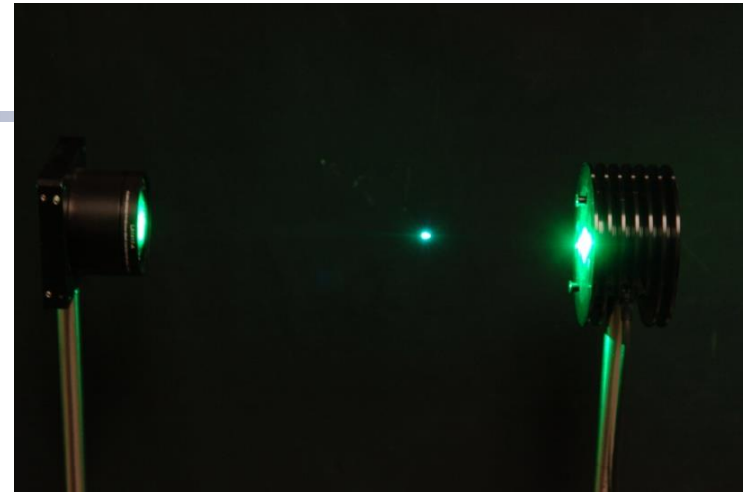
Schlieren Image showing interaction of shock waves thermal layer generated by laser induced plasma (Ref: Y. P. Raizer, Laser-induced discharge phenomena, ISBN 0-306-10923-9,1994)



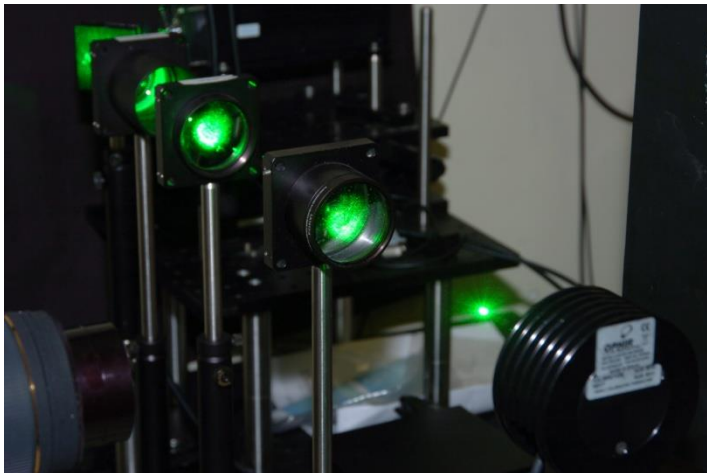
1a



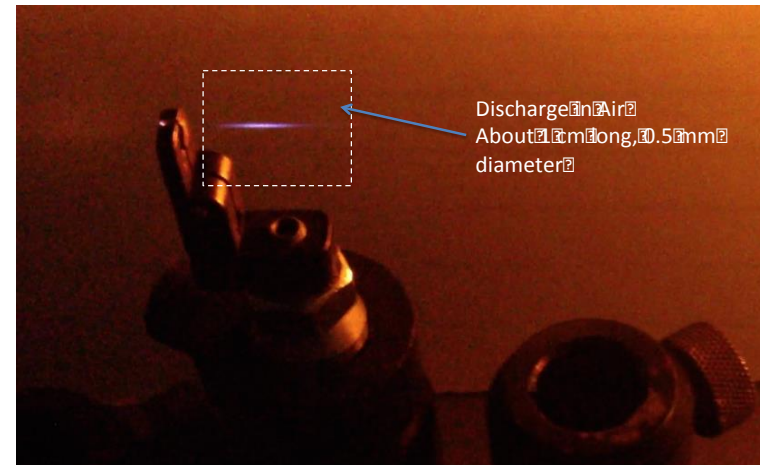
1b



1c



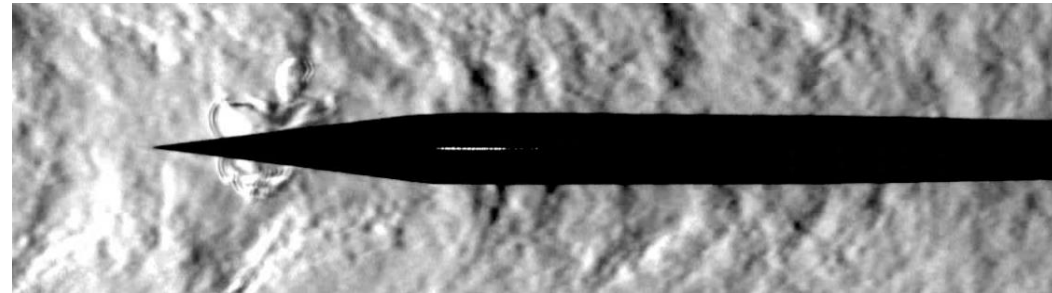
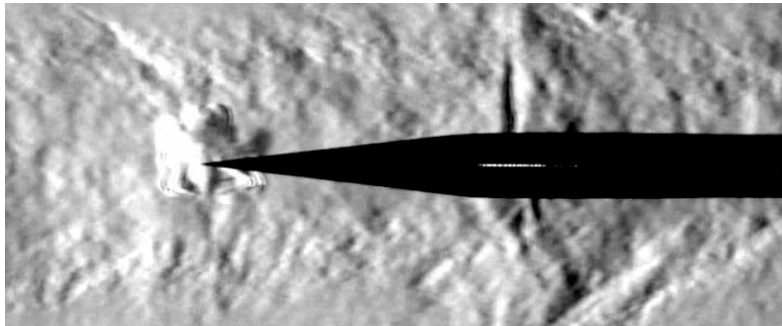
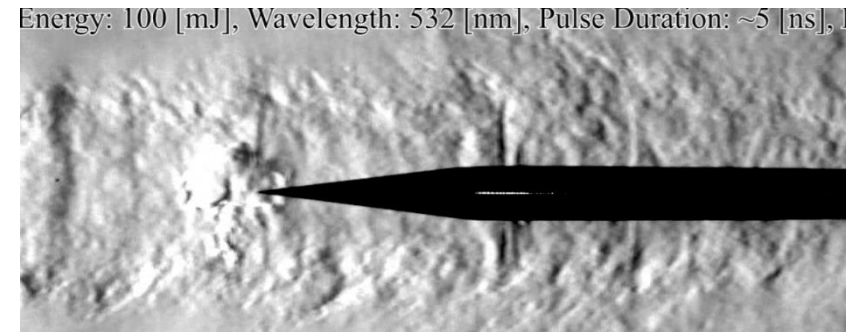
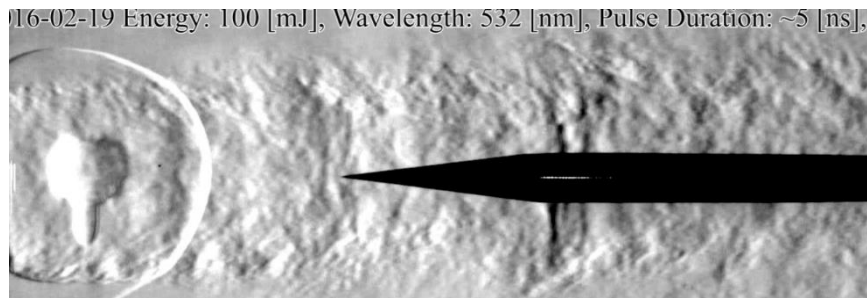
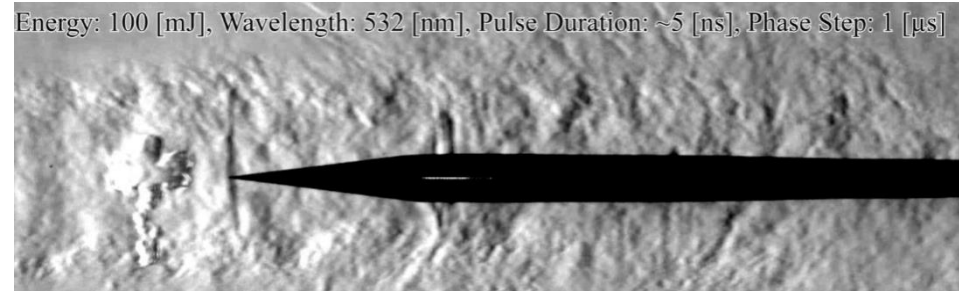
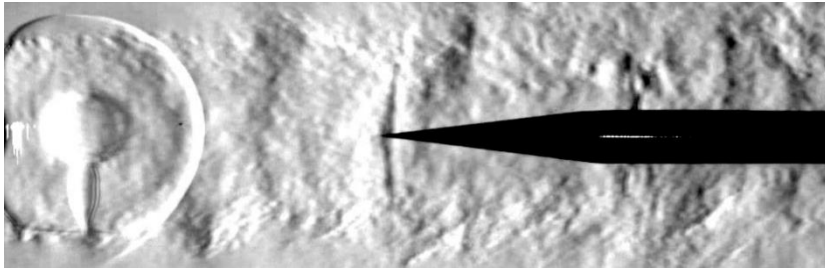
1d



**Nonequilibrium Plasmoids obtained by focusing Nd:YAG Nanosecond pulsed laser beam: 532nm, 5-30mJ, 4-5 nanosecond pulses at 25Hz. Fig 1a - 1c: Laser induced plasmoid (green spot): Plasmoids obtained by focusing Nd:YAG Nanosecond pulsed laser beam: 532nm, 5-30mJ, 4-5 nanosecond pulses at 20Hz. Laser has > than 400mJ capability.**

**FIG 1d: Laser filaments were generated by focusing a Femtosecond Ti-Sapphire laser beam, 1-12 mJ, 30 fs width, 500 Hz repetition rate. Filament is 1-2 cm long. Filaments produced by field ionization of room air. Demonstration at the University of Michigan, Ann Arbor.**

## Interaction of a Laser-induced plasmoid with sharp model: Mach 1.6



Free jet from a convergent nozzle. Facility uses shop air. Visualization is by a **dual-pulse Schlieren system ( $t < 5\text{ms}$ )** (as opposed to a time-average system) that is suited for recording highly unsteady phenomena. Dual-pulse Schlieren is synced to plasma YAG laser to capture shock interaction history. **Blast wave (detonation shockwave)** is clearly seen. **The steady model bow shock ( $t > 10\text{ms}$ ) is destroyed.** ***These are very preliminary results!!!***



# Sonic Boom Mitigation Activities

## (1) Design/Laser-Induced Plasma Experiment: **Demonstration**. Plasmoid Generation of plasmoids by Focused Laser Beams

Demonstrate in laboratory environments the plasma generating technology using laser beams at sub-atmospheric pressures; Design the proof of concept experiment and conduct the verification in aerodynamic test facilities; Establish criteria for choice of pulsed laser. (Wavelength, power, operating regime, etc) Explore “plasma spot” properties. Laser “recharge” time, power requirements, focusing lens materials, vibration tolerance, etc. Halbach magnet array design.

**(2) Fluence Calculations:** Weak ionization threshold calculations from intensity of light in focusing laser beam. Geometrical layout of strategically-situated laser-induced plasma spots to significantly diffuse/dissipate or eliminate the shock systems they generate. Developing analytical and computational tools to analyze relationship between high speed aerodynamic flows, shocks, plasma-heat injection, and sonic boom; Establish Criteria for specification of choice of laser (nanosecond/femtosecond pulser), and its mode of operation via experiment and theory: in progress.

## **(3) FREE-JET Experiments(Bldg 77/ Lab 370)**

Mach 1.5 – 3, past slender blunt conical nose. (GRC Tunnels: 1X1, 8X6, etc).

The task will involve analytical and experimental study of plasma generation using laser beams. That will include selection of laser sources, design of the experiment, and conduction of experiments to verify the optimal conditions for plasma generation.

To demonstrate the principle of laser generation by laser beams we will use an existing facility at GRC. Specifically, we will use the sub-atmospheric vacuum chamber in Bldg. 77 Rm.10.

**(4) Analytical Studies:** Weak ionization threshold calculations from intensity of light in focusing laser beam. Geometrical layout of **strategically-situated laser-induced plasma spots** to significantly diffuse/dissipate or eliminate the shock systems they generate. Developing analytical and computational tools to analyze relationship between high speed aerodynamic flows, shocks, plasma-heat injection, and sonic boom; Establish Criteria for specification of choice of laser (nanosecond/femtosecond pulser), and its mode of operation via experiment and theory: in progress.

**Develop a practical and scalable forward energy deposition method!!**

# **Space mission application:**

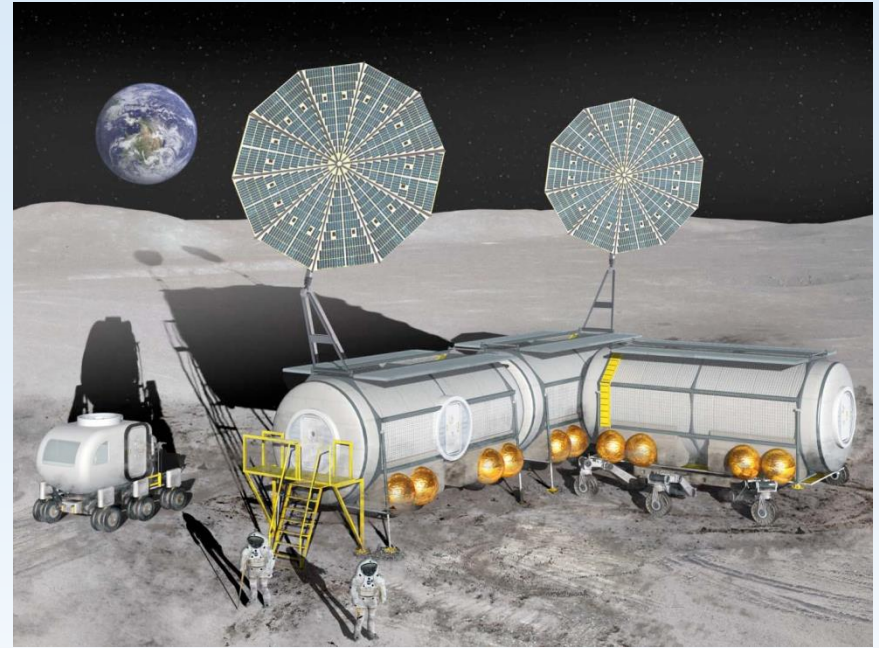
**Non-equilibrium plasma water  
purification supporting human  
space flight.**

**Injection of Repetitive High-Voltage  
Nanosecond Plasma in dielectric liquids  
(water, hydrocarbon fuels, etc)**



# Nonequilibrium Plasma-Based Water Treatment Technology Addresses **NASA mission** needs as well **Terrestrial Clean-Water Availability in a Variety of Venues**

- **Water resource use/reuse** on **ISS (87%)**, and long-duration missions (Mars)
  - Alternative to filtration and bio-reactor approaches
  - Simplified implementation
- **Environment** (“Green”) **Protection of the Great Lakes, ship ballast water, chicken/hog farms (pH)**
  - **Pre-treatment** of contaminants before emission into harbors, rivers and streams
    - Textile dyes, VOCs, invasive microbes
- **Point-of-use** water treatment for all countries, and **Military base camps**
  - Straightforward integration in areas without significant water treatment infrastructure



**Plasma treatment leads to decomposition of organic compounds in water and destruction of viruses, yeast, bacteria, e-coli, and other microorganisms.**



# Water Purification by Non-Thermal Plasma Treatment

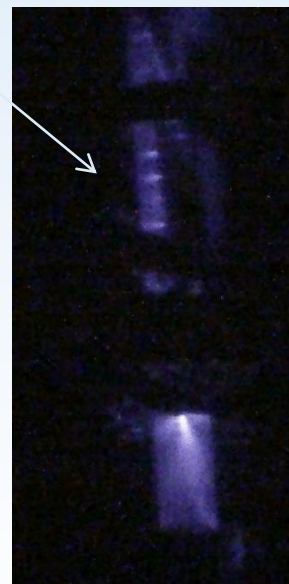
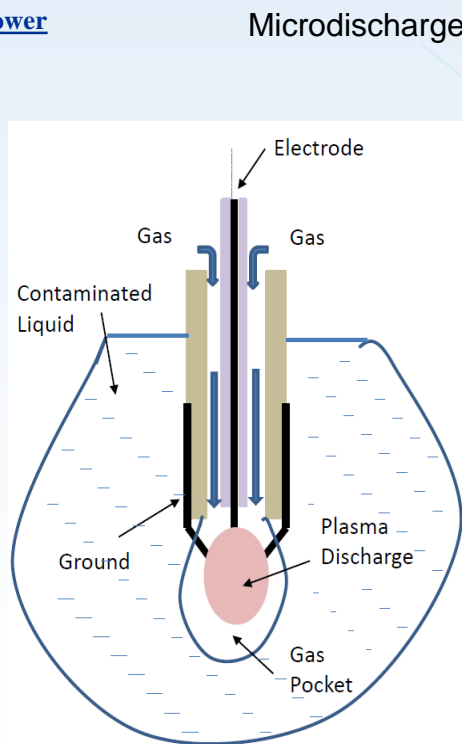
## Discharge Evolution/Species Evolution

- **Pulsed Repetitive High-Voltage Nanosecond non-equilibrium, non-thermal plasma** discharge produces the following dominant highly-reactive species: **H<sub>2</sub>O<sub>2</sub>, OH, O, O<sub>3</sub>, N<sub>2</sub>, e, etc.** In addition the discharge produces extremely high **E-fields, UV radiation, and shockwaves.**
- Discharge undergoes series of transitions with increasing voltage (~10 kHz): Corona-to avalanche-to streamer--- Streamer is associated with high chemical reactivity

### Oxidizing Species

### Relative Oxidation Power

CHLORINE	1.00
HYPOCHLOROUS ACID	1.10
HYDROGEN PEROXIDE	1.31
OZONE	1.52
ATOMIC OXYGEN	1.78
HYDROXYL RADICAL	2.05



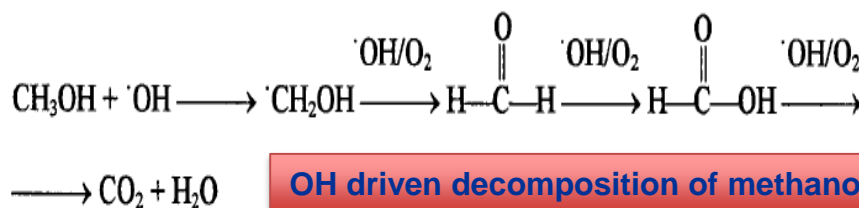
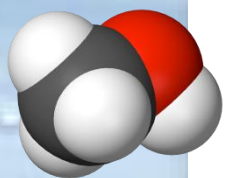
Glow/Avalanche  
with microdischarges  
Voltage= 10 kV



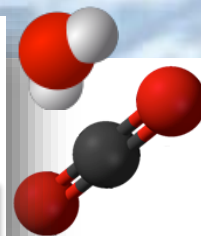
Streamers and microdischarge  
Voltage= 17 kV

# *Plasma generated advanced oxidation processes decompose toxins not addressed by conventional treatment methods*

Toxin	Purpose	Human Toxicology
Halogenated hydrocarbons	Industrial solvents	Possible birth defects; suppression of central nervous system
Aromatic compounds (e.g. benzene, toluene)	Chemical intermediate for synthesis of plastics and polymers	Known carcinogen (e.g. leukemia)
Pentachlorophenol (PCP)	Electrical insulating oils	Cancer causing; disrupts hormones
Pesticides	Agriculture	Linked to birth defects, nervous system damage, lymphoma, and cancer
Pharmaceuticals	Health care	Can lead to antibiotic resistant microbes; affect human hormonal balance
Cyanide	Mining, industrial chemical processing	Poison; disrupts cellular respiration

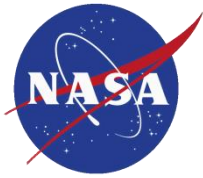


**OH driven decomposition of methanol**





# WHAT'S NEXT?



**The high-voltage, nanosecond pulse duration, capacitively-coupled discharge provides a mechanism for the production active species, such as atoms and electronically excited molecules in non-equilibrium gas plasmas.**

**Pursue the understanding of fundamental mechanisms affecting the design and operation of novel plasma-assisted reactive systems in dielectric liquids.**

## **EXPLOIT THE ABOVE CAPABILITY FOR:**

- (1) Injection of Repetitive High-Voltage Nanosecond Plasma in dielectric liquids (water, hydrocarbon fuels, etc). For propulsion, energize/modify heavy hydrocarbon fuels before combustion**
- (2) Plasma chemical dissociation hydrocarbons (in their own vapor or in mixtures with water vapor) for heavy hydrocarbon fuel reforming into lighter fractions, or for hydrogen generation.**
- (3) Water-recycling in long-duration missions to Mars.**
- (4) On-demand production of liquid fertilizer in long-duration missions to Mars.**
- (5) Low-energy salt-water desalination by plasma.**

**Encourage collaborations with academe and industry.**



# END

## BACKUP SLIDES



# Experimental Work and Apparatus

**Task Title:** Efficient Ionization Technology for the Plasma Environment

**Task Objective:** Understand the physics of the cold, non-equilibrium plasma generation in air and provide data for a multi-temperature model development to be used for evaluating its effectiveness in hypersonic flow control, heat transfer reduction, power generation, and noise suppression

**Technical Approach:**

- **Pulser-sustainer technique** chosen for the generation of cold, non-equilibrium air plasmas
  - Measure voltage-current characteristics of discharge circuits
  - Measure average electron density and temperature with Langmuir probes
  - Spectroscopically analyze collisional energy transfer processes
  - Quantify temporal characteristics of electron number density and temperature between pulses using millimeter wave (MMW) interferometry

**Results to date:**

- Pulser-sustainer plasmas generated over a range of vacuum conditions with  $10^{10} \text{ cm}^{-3}$  electron density
- Visible emission decay in 10-15 nsec range recorded with a gated intensified CCD camera
- Components of a millimeter wave (MMW) interferometric diagnostic acquired and installed
- A 0.5 m spectrometer with a PMT and an ICCD installed
- **Sub-atmospheric conditions set by Mach 7 flight at 30 km**
- **Bell jar with mechanical pump and dry air source assembled for 10 to 80 Torr**
- **High voltage pulser power supply with 10 to 60 kV amplitude, 2 ns rise, 5 ns width, 3 ns fall, and 6 to 100 kHz repetition rate**
- **Sustainer floating power supply with 2 kV and 3 A**
- **ICCD camera with variable delay resolution down to 2.5 ps**
- **500 MHz digital phosphor oscilloscope**
- **75 MHz voltage probe with 4 ns rise time**
- **DC to 50 MHz current probe with 7 ns rise time**